TRACING VERY HIGH ENERGY TAU NEUTRINOS FROM COSMOLOGICAL SOURCES IN ICE

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Astrophysical sources of ultrahigh energy neutrinos yield tau neutrino fluxes due to neutrino oscillations. We study in detail the contribution of tau neutrinos with energies above 10^6 GeV relative to the contribution of the other flavors. We consider several different initial neutrino fluxes and include tau neutrino regeneration in transit through the Earth and energy loss of charged leptons. We discuss signals of tau neutrinos in detectors such as IceCube, RICE and ANITA.

1. Introduction

The experimental evidence of $\nu_\mu \leftrightarrow \nu_\tau$ neutrino oscillations [1] means that astrophysical sources of muon neutrinos become sources of ν_μ and ν_τ in equal proportions after oscillations over astronomical distances [2]. Although ν_μ and ν_τ have identical interaction cross sections at high energies, signals from $\nu_\tau \to \tau$ conversions have the potential to contribute differently from ν_μ signals. The τ lepton can decay far from the detector, regenerating ν_τ [3]. This also occurs with μ decays, but electromagnetic energy loss coupled with the long muon lifetime make the ν_μ regeneration from muon decays irrelevant for high energies. A second signal of $\nu_\tau \to \tau$ is the tau decay itself [4].

We have studied in detail the propagation of all flavors of neutrinos with very high energy ($E \geq 10^6$ GeV) as they traverse the Earth. Because of the high energies attenuation shadows most of the upward-going solid angle at high energies, so we have limited our consideration to nadir angles

larger than 80°. We are particularly interested in the contribution from tau neutrinos, produced in oscillations of extragalactic muon neutrinos as they travel large astrophysical distances.

For most astrophysical sources, the neutrinos are produced in pion decays, which determine the flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ to be $1 : 2 : 0$. After propagation over very long distances, neutrino oscillations change this ratio to $1 : 1 : 1$ because of the maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing. For the GZK flux, ν_e and ν_μ incident fluxes are different because of the additional contributions from $\bar{\nu}_e$ from neutron decay and ν_e from μ^+ decays [5]. Because of this, the flavor ratio at Earth is affected by the full three flavor mixing and is different from $1 : 1 : 1$. Given fluxes at the source $F^0_{\nu_e}$, $F^0_{\nu_\mu}$ and $F^0_{\nu_\tau}$, the fluxes at Earth become:

$$F_{\nu_e} = F^0_{\nu_e} - \frac{1}{4}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau}) \tag{1}$$

$$F_{\nu_\mu} = F_{\nu_\tau} = \frac{1}{2}(F^0_{\nu_\mu} + F^0_{\nu_\tau}) + \frac{1}{8}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau}) \tag{2}$$

where θ_{12} is the mixing angle relevant for solar neutrino oscillations. We have assumed that θ_{23}, the mixing angle relevant for atmospheric neutrino oscillations, is maximal and θ_{13} is very small, as shown by reactor experiments, as well as atmospheric and solar data.

Z burst neutrinos[6] from models with ultrahigh energy neutrinos scattering with relic neutrinos to produce Z bosons is another neutrino flux considered below, where neutrino mixing yields flux ratios of $1 : 1 : 1$.

The initial fluxes for GZK and Z burst neutrinos are shown in Fig. 1.

In our propagation of neutrinos and charged leptons through the Earth[7], we have focused on kilometer-sized neutrino detectors, such as ICECUBE [8] and the Radio Ice Cerenkov Experiment (RICE)[9] and on a detector with much larger effective area which uses Antarctic ice as a converter, the Antarctic Impulsive Transient Antenna (ANITA)[10].

2. Neutrino Propagation

Attenuation and regeneration of neutrinos and charged leptons are governed by the following transport equations:

$$\frac{\partial F_{\nu_\tau}(E,X)}{\partial X} = -N_A\sigma^{tot}(E)F_{\nu_\tau}(E,X) + N_A\int_E^\infty dE_y F_{\nu_\tau}(E_y,X)\frac{d\sigma^{NC}}{dE}(E_y,E) + \int_E^\infty dE_y \frac{F_\tau(E,X)}{\lambda_\tau^{dec}}\frac{dn}{dE}(E_y,E) \tag{3}$$

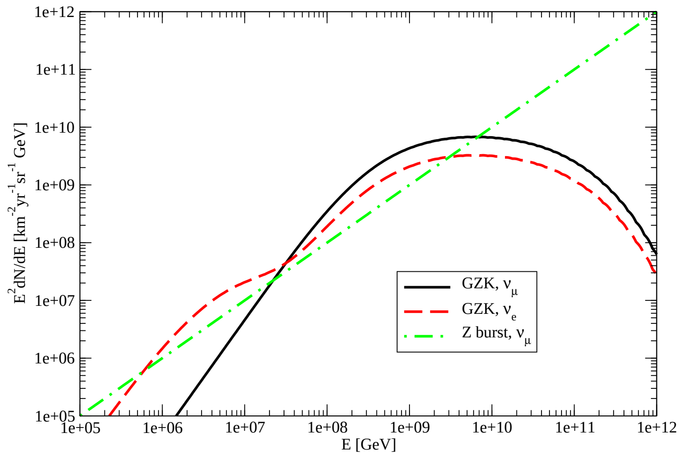

Figure 1. Initial Neutrino Fluxes

$$\frac{\partial F_\tau(E,X)}{\partial X} = -\frac{F_\tau(E,X)}{\lambda_\tau^{dec}(E,X,\theta)} + N_A \int_E^\infty dE_y F_{\nu_\tau}(E_y,X) \frac{d\sigma^{CC}}{dE}(E_y,E) \quad (4)$$

$$-\frac{dE_\tau}{dX} = \alpha + \beta E_\tau \quad (5)$$

Here $F_{\nu_\tau}(E,X) = dN_{\nu_\tau}/dE$ and $F_\tau(E,X) = dN_\tau/dE$ are the differential energy spectra of tau neutrinos and taus respectively, for lepton energy E, at a column depth X in the medium defined by

$$X = \int_0^L \rho(L')dL'. \quad (6)$$

For tau neutrinos, we take into account the attenuation by charged current interactions, the shift in energy due to neutral current interactions and the regeneration from tau decay. For tau leptons we consider their production in charged current ν_τ interactions, their decay, as well as electromagnetic energy loss.

The effective decay length of produced taus does not go above 10^7 cm, even for $E_\tau = 10^{12}$ GeV. This is because electromagnetic energy loss over that distance reduces the tau energy to about 10^8 GeV, at which point the tau is more likely to decay than interact electromagnetically [11].

We have found that the ν_τ flux above 10^8 GeV resembles the ν_μ flux. The lore that the Earth is transparent to tau neutrinos is not applicable in the high energy regime. Tau neutrino pileups at small angles with respect

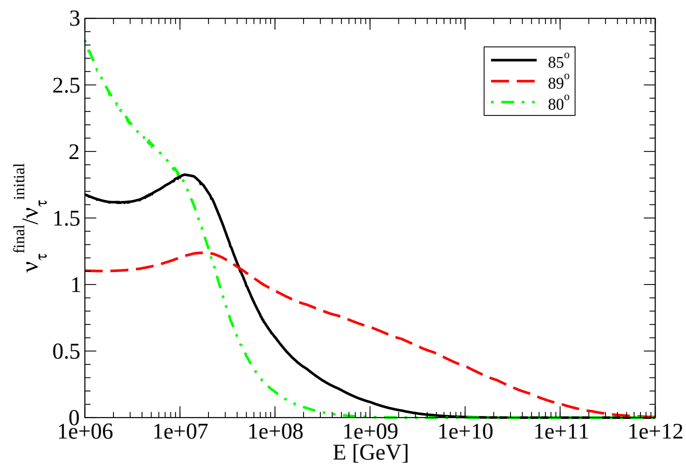

Figure 2. Ratio ν_τ/ν_μ for GZK neutrinos, at nadir angles of 85° and 89°.

to the horizon are significantly damped due to tau electromagnetic energy loss above $E_\tau \sim 10^8$ GeV if the column depth is at least as large as the neutrino interaction length.

At lower energies, $E \leq 10^8$ GeV, regeneration of ν_τ becomes important for trajectories where the other flavors of neutrinos are strongly attenuated, but the ν_τ regeneration is very effective. The regeneration effect depends strongly on the shape of the initial flux and it is larger for flatter fluxes. The enhancement due to regeneration also depends on the amount of material traversed by neutrinos and leptons, i.e. on nadir angle. For GZK neutrinos, we have found that the enhancement peaks between 10^6 and a few$\times 10^7$ GeV depending on trajectory.

Fig. 2 shows the ratio of the tau neutrino flux after propagation to incident tau neutrino flux, for 89°, 85°and 80°. This ratio illustrates a combination of the regeneration of ν_τ due to tau decay and the attenuation of all neutrino fluxes. For 89°, where both the total distance and the density are smaller, the attenuation is less dramatic, and the flux can be significant even at high energy. The regeneration in this case can add about 25% corrections at energies between 10^7 and 10^8 GeV. For 85° the relative enhancement is around 80% and peaked at slightly lower energies, while at 80° it is almost a factor of 3 at low energy. At 80°, however, the flux is very strongly attenuated for energies above a few $\times 10^7$ GeV. It is already clear from here that the total rates will be dominated by the nearly horizontal trajectories that go through a small amount of matter. However, rates can

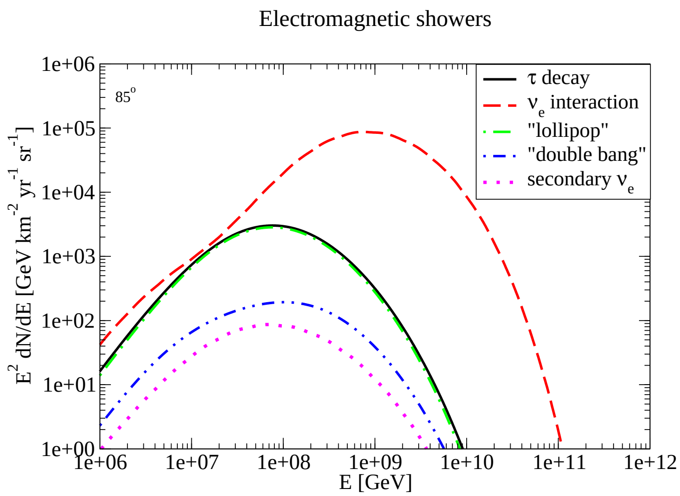

Figure 3. Electromagnetic showers for GZK neutrinos

get significant enhancements at low energies where the regeneration from tau decays adds an important contribution even for longer trajectories.

3. Showers

We have translated the neutrino fluxes and tau lepton fluxes into rates for electromagnetic and hadronic showers at selected angles to see the effect of attenuation, regeneration, and the different energy dependences of the incident fluxes. We have focused on comparing the ν_τ contribution to the ν_e and ν_μ contributions to determine in what range, if any, ν_τ's enhance shower rates. Electromagnetic shower distributions for a nadir angle of 85° are shown in Fig. 3, while Fig. 5 shows hadronic showers.

Fig. 4 shows the ratio of the electromagnetic shower rates at nadir angle 85° in the presence and absence of oscillations for the GZK and Z burst neutrino fluxes (which have a characteristic $1/E$ energy dependence). In absence of oscillations, the only contribution to electromagnetic showers comes from ν_e interactions. In the presence of $\nu_\mu \to \nu_\tau$ oscillations, electromagnetic decays of taus from tau neutrinos add significant contributions to these rates at energies below 10^8 GeV. In the same time, for the GZK flux, $\nu_e \to \nu_{\mu,\tau}$ oscillations reduce the number of ν_e's at low energy, such that below a few $\times 10^6$ GeV there are fewer electromagnetic showers than in the absence of oscillations.

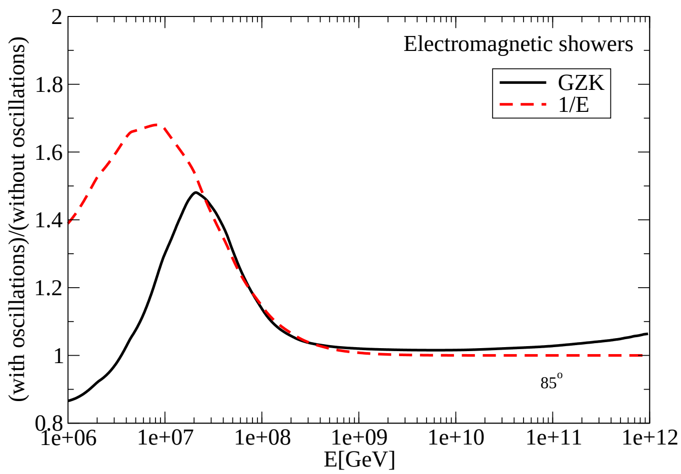

Figure 4. Ratio of electromagnetic shower rates in the presence and absence of $\nu_\mu \rightarrow \nu_\tau$ oscillations for GZK and $1/E$ neutrino spectra for nadir angle 85° for a km size detector.

The ν_τ flux enhancements depend on the shape of the initial flux. The electromagnetic showers are more sensitive to this shape than hadronic ones. The relative enhancement in hadronic showers is also smaller than for the electromagnetic showers. This is because for the electromagnetic signal the only contribution in the absence of taus is from electron neutrinos, while for hadrons the tau contribution is compared to a much larger signal, from the interactions of all flavors of neutrinos. We have included contribution from secondary neutrinos, which we find to be relatively small for all fluxes.

For kilometer-sized detectors, at for example a nadir angle of 85°, the maximal enhancement due to ν_τ contribution to electromagnetic shower rates for the GZK flux is about 50% at 3×10^7 GeV, while for a $1/E$ flux, it is even larger, about 70%, at slightly lower energy. These energy ranges are relevant for IceCube, but not for RICE. For energies relevant to RICE, tau neutrinos do not offer any appreciable gain in electromagnetic shower signals compared to $\nu_e \rightarrow e$ CC interactions, and they contribute at essentially the same level as ν_μ to hadronic shower rates through NC interactions.

One of the reasons that tau neutrinos do not contribute large signals to kilometer-sized detectors at very high energies is that high energy tau decay lengths are very large, so the probability of a tau decaying in the detector is low. For detectors like ANITA which can sample long trajectories through the ice, one would expect a larger tau neutrino contribution to the signal

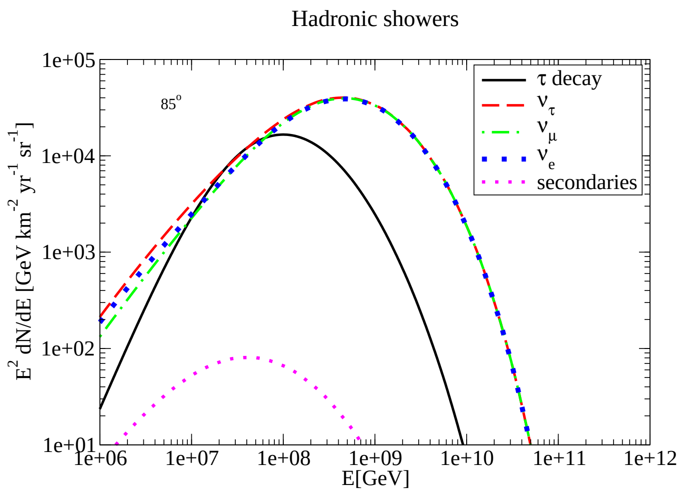

Figure 5. Hadronic showers for GZK neutrinos

from tau decay. Despite the long trajectory (222 km with a maximum depth of 1 km for a neutrino incident at 89° nadir angle) the tau contributions to the electromagnetic shower rate is quite small for fluxes expected to contribute in the ANITA signal. For hadronic showers, the suppression of τ decay to hadrons relative to ν_e NC interaction contributions is about the same as for electromagnetic showers compared to $\nu_e \rightarrow e$. The ν_τ contribution to the hadronic shower rate from interactions is about the same as the ν_e contribution. In summary, for ANITA, tau neutrinos do not give any additional signal beyond what one would evaluate based on no regeneration from $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$ due to tau electromagnetic energy loss at $E \gtrsim 10^8$ GeV.

Acknowledgments

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